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Comparisons of Exact Amplitude–Based Resummation Predictions and LHC Data

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Abstract

Using the MC Herwiri1.031, we present the current status of the comparisons with LHC data of the predictions of our approach of exact amplitude-based resummation for precision QCD calculations.

Keywords: QCD Resummation IR-Improved DGLAP-CS Theory NLO-PS MC

1. Introduction

The successful running of the LHC during 2010-2012 has resulted in large data samples on SM standard candle processes such as heavy gauge boson production and decay to lepton pairs (samples exceeding 10^7 of such events for Z/γ^* production) for ATLAS and CMS. Such data signal the arrival of the era of precision QCD, with predictions for QCD processes at the total precision tag of 1% or better, and make more manifest the need for exact, amplitude-based resummation of large higher order effects as discussed in Refs. [1]. Such precision allows one to distinguish new physics(NP) from higher order SM processes and to distinguish different models of new physics from one another as well. We present here comparisons of the attendant application of exact amplitude-based resummation theory to recent data from the LHC. We first review the elements our approach as formulated in Ref. [2] before we turn in the next section to comparisons with recent LHC data.

Our starting point is the well-known representation

$$d\sigma = \sum_{i,j}\int dx_1 dx_2 F_i(x_1)F_j(x_2)d\hat{\sigma}_{\rm res}(x_1x_2s) \qquad (1)$$

of a hard LHC scattering process, where $\{F_j\}$ and $d\hat{\sigma}_{\rm res}$ are the respective parton densities (PDF's) and reduced resummed hard differential cross section. The resummation includes all large EW and QCD higher order corrections as needed for achieving a total precision tag of 1% or better for the total theoretical precision of (1). The total theoretical precision $\Delta\sigma_{\rm th}$ of (1) as defined in Refs. [3, 4] is essential to the faithful application of any theoretical prediction to precision experimental data. Whenever $\Delta\sigma_{\rm th} \leq f\Delta\sigma_{\rm expt}$, where $\Delta\sigma_{\rm expt}$ is the respective experimental error and $f \lesssim \frac{1}{2}$, the theoretical uncertainty will not adversely affect the physics analysis of the data. With our eye on a provable theoretical precision tag we have developed the QCD $\otimes$ QED resummation theory in Refs. [2] for (1). The key exact master formula is

$$d\bar{\sigma}_{\rm res} = e^{\rm SUM_{IR}(QCED)}\sum_{n,m=0}^{\infty}\frac{1}{n!m!}\int\prod_{j_1=1}^{n}\frac{d^3k_{j_1}}{k_{j_1}} \prod_{j_2=1}^{m}\frac{d^3k'_{j_2}}{k'_{j_2}}\int\frac{d^4y}{(2\pi)^4}e^{iy\cdot(p_1+q_1-p_2-q_2-\sum k_{j_1}-\sum k'_{j_2})+D_{\rm QCED}} \tilde{\bar{\beta}}_{n,m}(k_1,\ldots,k_n;k'_1,\ldots,k'_m)\frac{d^3p_2}{p_2^0}\frac{d^3q_2}{q_2^0}. \qquad (2)$$

Here $d\bar{\sigma}_{\rm res}$ is either the reduced cross section $d\hat{\sigma}_{\rm res}$ or the differential rate associated to a DGLAP-CS [5, 6] kernel involved in the PDF evolution and the *new* (YFS-style [7, 8]) *non-Abelian* residuals $\tilde{\bar{\beta}}_{n,m}(k_1,\ldots,k_n;k'_1,\ldots,k'_m)$ have n hard gluons and m hard photons and we show the generic $2f$ final state with momenta p_2, q_2 for definiteness. The infrared functions $\rm SUM_{IR}(QCED)$, $D_{\rm QCED}$ are given in Refs. [2, 9, 10]. The residuals $\tilde{\bar{\beta}}_{n,m}$ allow a rigorous par-

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ton shower/ME matching via their shower-subtracted counterparts $\hat{\bar{\tilde{\beta}}}_{n,m}$ [2].

We now discuss the paradigm opened by (2) for precision QCD via comparisons with recent data.

2. Comparisons to Data of Precision QCD for the LHC

We first recall that, as we have discussed in Refs. [1], the methods we employ are fully consistent with the methods in Refs. [11, 12, 13, 14, 15, 16] but we do not have intrinsic physical physical barriers to sub-1precision as do the approaches used in the latter references. They may used to give approximations to our new residuals $\tilde{\bar{\beta}}_{m,n}$ for studies of consistency [17].

With this understanding, we note that, if we apply (2) to the calculation of the kernels, P_{AB}, we arrive at an improved IR limit of these kernels, IR-improved DGLAP-CS theory . In this latter theory [9, 10] large IR effects are resummed for the kernels themselves. From the resulting new resummed kernels, P^{exp}_{AB} [9, 10] we get a new resummed scheme for the PDF's and the reduced cross section: $F_j,\ \hat{\sigma} \rightarrow F'_j,\ \hat{\sigma}'$ for $P_{gq}(z) \rightarrow P^{\exp}_{gq}(z) = C_F F_{YFS}(\gamma_q) e^{\frac{1}{2}\delta_q} \frac{1+(1-z)^2}{z} z^{\gamma_q}$, etc.. This new scheme gives σ in (1) with improved MC stability [1]. Here, C_F is the quadratic Casimir invariant for the quark color representation. See Refs. [9, 10] for the definitions of $F_{YFS}, \gamma_q,\ \delta_q$ as well as for the complete set of results for the new P^{exp}_{AB}.

The physical idea underlying the new kernels was shown by Bloch and Nordsieck [18]: due to the coherent state of very soft massless gauge field quanta generated by an accelerated charge it impossible to know which of the infinity of possible states one has made in the splitting process $q(1) \rightarrow q(1-z) + G \otimes G_1 \cdots \otimes G_\ell,\ \ell = 0, \cdots, \infty$. The new kernels take this effect into account by resumming the terms $O((\alpha_s \ln(q^2/\Lambda^2)\ln(1-z))^n)$ for the IR limit $z \rightarrow 1$. This resummation generates [1, 9, 10] the Gribov-Lipatov exponents γ_A which start in $O(\hbar)$ in the loop expansion [1].

The first realization of the new IR-improved kernels is given by new MC Herwiri1.031 [1] in the Herwig6.5 [20] environment. Realization of the new kernels in the Herwig++ [21], Pythia8 [22], Sherpa [23] and Powheg [24] environments is in progress as well. In Fig. 1 we illustrate some of the recent comparisons we have made between Herwiri1.031 and Herwig6.510, both with and without the MC@NLO [25] exact $O(\alpha_s)$ correction[2] , in relation to the LHC data [26, 27] on $Z/\gamma*$ production with decay to lepton pairs[3]. Just as we found in Refs. [1] for the FNAL data

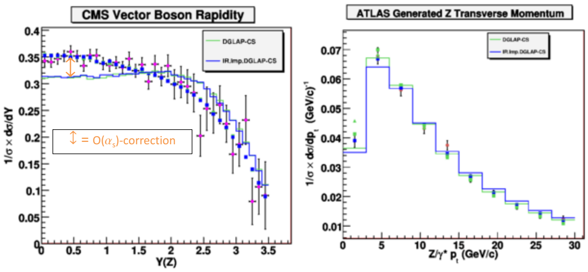

Figure 1: Comparison with LHC data: (a), CMS rapidity data on (Z/γ^*) production to e^+e^-, $\mu^+\mu^-$ pairs, the circular dots are the data, the green(blue) lines are HERWIG6.510(HERWIRI1.031); (b), ATLAS p_T spectrum data on (Z/γ^*) production to (bare) e^+e^- pairs, the circular dots are the data, the blue(green) lines are HERWIRI1.031(HERWIG6.510). In both (a) and (b) the blue(green) squares are MC@NLO/HERWIRI1.031(HERWIG6.510(PTRMS = 2.2GeV)). In (b), the green triangles are MC@NLO/HERWIG6.510(PTRMS =0). These are otherwise untuned theoretical results.

on single Z/γ^* production, the unimproved MC requires the very hard value of PTRMS $\cong$ 2.2GeV to give a good fit to the p_T spectra as well as the rapidity spectra whereas the IR-improved calculation gives very good fits to both of the spectra without the need of such a hard value of PTRMS, the rms value for an intrinsic Gaussian p_T distribution, for the proton wave function: the $\chi^2/d.o.f$ are respectively $(0.72, 0.72)$, $(1.37, 0.70)$, $(2.23, 0.70)$ for the p_T and rapidity data for the MC@NLO/HERWIRI1.031, MC@NLO/HERWIG6.510(PTRMS = 2.2GeV) and MC@NLO/HERWIG6.510(PTRMS =0) results. Such a hard intrinsic value of PTRMS contradicts the results in Refs. [30, 31], as we discuss in Refs. [1]. To illustrate the size of the exact $O(\alpha_s)$ correction, we also show the results for both Herwig6.510(green line) and Herwiri1.031(blue line) without it in the plots in Fig. 1. As expected, the exact $O(\alpha_s)$ correction is important for both the p_T spectra and the rapidity spectra. The suggested accuracy at the 10% level shows the need for the NNLO extension of MC@NLO, in view of our goals for this process. We also note that, with the 1% precision goal, one also needs per mille level control of the EW corrections. This issue is addressed in the new version of the $\mathcal{KK}$ MC [32], version 4.22, which now allows

[1] See Ref. [19] for the connection between the new kernels and the Wilson expansion.

[2] See Refs. [1] for the connection bewteen the $\hat{\bar{\tilde{\beta}}}_{n,m}$ and the MC@NLO differential cross sections.

[3] Similar comparisons were made in relation to such data [28, 29] from FNAL in Refs. [1].

for incoming quark antiquark beams – see Ref. [32] for further discussion of the relevant effects in relation to other approaches [33].

We have also made comparisons with recent LHCb data [34] on single Z/γ^* production and decay to lepton pairs. These results will be presented in detail elsewhere [17]. Here, we illustrate them with the results in Fig. 2 for the Z/γ^* rapidity as measured by LHCb for the decays to e^+e^- pairs and the decays to $\mu^+\mu^-$ pairs. These

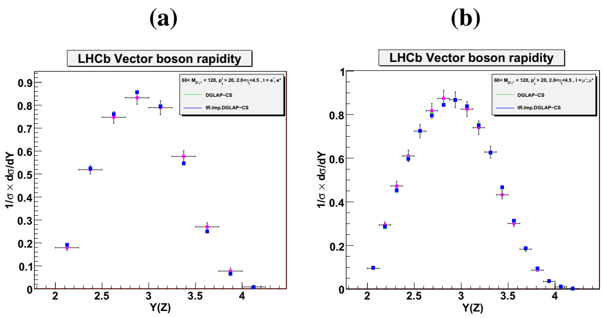

Figure 2: Comparison with LHC data: LHCb rapidity data on (Z/γ^*) production to (a) e^+e^-, (*b*) $\mu^+\mu^-$ pairs, the circular dots are the data. In both (a) and (b) the blue(green) squares are MC@NLO/HERWIRI1.031(HERWIG6.510(PTRMS = 2.2GeV)) and the green triangles are MC@NLO/HERWIG6.510(PTRMS =0). These are otherwise untuned theoretical results.

data probe a different phase space regime: the lepton pseudorapidity η satisfies $2.0 < \eta < 4.5$ to be compared with $|\eta_\ell| < 2.1(|\eta_\ell| < 2.4)$, $|\eta_{\ell'}| < 4.6(|\eta_{\ell'}| < 2.4)$ for the CMS(ATLAS) data in Fig. 1. Here $\eta_\ell(\eta_{\ell'})$ is the respective pseudorapidity of ℓ, $\ell = \mu, \bar{\mu}(\ell',\ \ell' = e, \bar{e})$, respectively. Again, the agreement between the IR-improved MC@NLO/Herewiri1.031 without the need of an ad hocly hard value of PTRMS is shown for both the $e\bar{e}$ and $\mu\bar{\mu}$ data, where the $\chi^2/d.o.f.$ are $0.746, 0.773$ respectively. The unimproved calculations with MC@NLO/Herwig6510 for PTRMS = 0 and PTRMS = 2.2 GeV respectively also give good fits, with the $\chi^2/d.o.f.$ of 0.814, 0.836 and 0.555, 0.537 respectively for the $e\bar{e}$ and $\mu\bar{\mu}$ data. In the phase space probed by the LHCb, it continues to hold that the more inclusive observables such as the normalized Z/γ^* rapidity spectrum are not as sensitive to the IR-improvement as observables such as the Z/γ^* p_T spectrum.

As one has now more than 10^7 $Z/\gamma*$ decays to lepton pairs per experiment at ATLAS and CMS, we show in Refs. [1] that one may use the new precision data to distinguish between the fundamental description in Herwiri1.031 and the ad hocly hard intrinsic p_T in Herwig6.5 by comparing the data to the predictions of the detailed line shape and of the more finely binned p_T spectra – see Figs. 3 and 4 in the last two papers in Refs. [1][4]. We await the availability of the new precision data accordingly.

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References

[1] S. Joseph *et al.*, Phys. Lett. B**685** (2010) 283; Phys. Rev. D**81** (2010) 076008; S. Majhi *et al.*, Phys. Lett. B**719** (2013) 367; arXiv:1305.0023.

[2] C. Glosser, S. Jadach, B.F.L. Ward and S.A. Yost, Mod. Phys. Lett. A **19**(2004) 2113; B.F.L. Ward, C. Glosser, S. Jadach and S.A. Yost, in *Proc. DPF 2004*, Int. J. Mod. Phys. A **20** (2005) 3735; in *Proc. ICHEP04, vol. 1*, eds. H. Chen *et al.*,(World. Sci. Publ. Co., Singapore, 2005) p. 588; B.F.L. Ward and S. Yost, preprint BU-HEPP-05-05, in *Proc. HERA-LHC Workshop*, CERN-2005-014; in *Moscow 2006, ICHEP, vol. 1*, p. 505; Acta Phys. Polon. B **38** (2007) 2395; arXiv:0802.0724, PoS(**RADCOR2007**)(2007) 038; B.F.L. Ward *et al.*, arXiv:0810.0723, in *Proc. ICHEP08*; arXiv:0808.3133, in *Proc. 2008 HERA-LHC Workshop*,DESY-PROC-2009-02, eds. H. Jung and A. De Roeck, (DESY, Hamburg, 2009)pp. 180-186, and references therein.

[3] See for example S. Jadach *et al.*, in *Physics at LEP2, vol. 2*, (CERN, Geneva, 1995) pp. 229-298.

[4] B.F.L. Ward, S.K. Majhi and S.A. Yost, PoS(**RADCOR 2011**) (2012) 022.

[5] G. Altarelli and G. Parisi, *Nucl. Phys.* **B126** (1977) 298; Yu. L. Dokshitzer, *Sov. Phys. JETP* **46** (1977) 641; L. N. Lipatov, *Yad. Fiz.* **20** (1974) 181; V. Gribov and L. Lipatov, *Sov. J. Nucl. Phys.* **15** (1972) 675, 938; see also J.C. Collins and J. Qiu, *Phys. Rev. D***39** (1989) 1398.

[6] C.G. Callan, Jr., *Phys. Rev. D***2** (1970) 1541; K. Symanzik, *Commun. Math. Phys.* **18** (1970) 227, and in *Springer Tracts in Modern Physics*, **57**, ed. G. Hoehler (Springer, Berlin, 1971) p. 222; see also S. Weinberg, *Phys. Rev. D***8** (1973) 3497.

[7] D. R. Yennie, S. C. Frautschi, and H. Suura, Ann. Phys. **13** (1961) 379; see also K. T. Mahanthappa, Phys. Rev. **126** (1962) 329, for a related analysis.

[8] S. Jadach and B.F.L. Ward, Phys. Rev. **D38** (1988) 2897;*ibid.* **D39** (1989) 1471; *ibid.* **D40** (1989) 3582; S.Jadach, B.F.L. Ward and Z. Was, Comput. Phys. Commun. **66** (1991) 276; S.Jadach and B.F.L. Ward, Phys. Lett. **B274** (1992) 470; S. Jadach *et al.*, Comput. Phys. Commun. **70** (1992) 305; S.Jadach, B.F.L. Ward and Z. Was, Comput. Phys. Commun. **79** (1994) 503;*ibid.***124** (2000) 233; *ibid.***130** (2000) 260; Phys. Rev. D 63 (2001) 113009; S. Jadach *et al.*, Phys. Lett. **B353** (1995) 362; *ibid.* **B384** (1996) 488; Comput. Phys. Commun. **102** (1997) 229; S.Jadach, W. Placzek and B.F.L. Ward, Phys. Lett. **B390** (1997) 298; Phys. Rev. **D54** (1996) 5434; Phys.Rev. D56 (1997) 6939; S.Jadach, M. Skrzypek and B.F.L. Ward, Phys. Rev. **D55**

[4] The discriminating power among the attendant theoretical predictions of p_T spectra in single Z/γ^* production at the LHC is manifest in Refs. [35]– the last paper in Refs. [1] provides more discussion on this point.

(1997) 1206; S. Jadach *et al.*, Phys. Lett. **B417** (1998) 326; Comput. Phys. Commun. **119** (1999) 272; *ibid.* **140** (2001) 432, 475; Phys. Rev. **D61** (2000) 113010; *ibid.* **D65** (2002) 093010.
[9] B.F.L. Ward, *Adv. High Energy Phys.* **2008** (2008) 682312.
[10] B.F.L. Ward, *Ann. Phys.* **323** (2008) 2147.
[11] G. Sterman,*Nucl. Phys.* **B281** (1987) 310; S. Catani and L. Trentadue, *ibid.* **B327** (1989) 323; *ibid.* **B353** (1991) 183.
[12] See for example C. W. Bauer, A.V. Manohar and M.B. Wise, *Phys. Rev. Lett.* **91** (2003) 122001; *Phys. Rev.* **D70** (2004) 034014; C. Lee and G. Sterman, *Phys. Rev. D* **75** (2007) 014022.
[13] J.C. Collins and D.E. Soper, Nucl. Phys. B**193** (1981) 381; *ibid.***213**(1983) 545; *ibid.* **197**(1982) 446; J.C. Collins, D.E. Soper and G. Sterman, Nucl. Phys. B**250**(1985) 199; in *Les Arcs 1985, Proceedings, QCD and Beyond*, pp. 133-136.
[14] C. Balazs and C.P. Yuan, Phys. Rev. D**56** (1997) 5558; G.A. Ladinsky and C.P. Yuan, Phys. Rev. D**50** (1994) 4239; F. Landry *et al.*, Phys. Rev. D**67** (2003) 073016.
[15] A. Banfi *et al.*, Phys. Lett. B**715** (2012) 152.
[16] T. Becher, M. Neubert and D. Wilhelm, arXiv:1109.6027; T. Becher and M. Neubert, Eur. Phys. J. C**71** (2011) 1665.
[17] A. Mukhopadhyayi *et al.*, to appear.
[18] F. Bloch and A. Nordsieck, Phys. Rev. **52** (1937) 54.
[19] B.F.L. Ward, Mod. Phys. Lett. A**28**(2013) 1350069.
[20] G. Corcella *et al.*, hep-ph/0210213; J. High Energy Phys. **0101** (2001) 010; G. Marchesini *et al.*, Comput. Phys. Commun.**67** (1992) 465.
[21] M. Bahr *et al.*, arXiv:0812.0529 and references therein.
[22] T. Sjostrand, S. Mrenna and P. Z. Skands, Comput. Phys. Commun. **178** (2008) 852-867.
[23] T. Gleisberg *et al.*, J.High Energy Phys. **0902** (2009) 007.
[24] P. Nason, J. High Energy Phys. **0411** (2004) 040.
[25] S. Frixione and B.Webber, J. High Energy Phys. **0206** (2002) 029; S. Frixione *et al.*, arXiv:1010.0568.
[26] S. Chatrchyan *et al.*, Phys. Rev. D**85** (2012) 032002.
[27] G. Aad *et al.*, arXiv:1107.2381; Phys. Lett. B**705** (2011) 415.
[28] V.M. Abasov et al., Phys. Rev. Lett. **100** (2008) 102002.
[29] C. Galea, in *Proc. DIS 2008*, London, 2008, http://dx.doi.org/10.3360/dis.2008.55.
[30] R.P. Feynman, M. Kislinger and F. Ravndal, Phys. Rev. D**3** (1971) 2706; R. Lipes, *ibid.***5** (1972) 2849; F.K. Diakonos, N.K. Kaplis and X.N. Maintas, *ibid.* **78** (2008) 054023; K. Johnson, *Proc. Scottish Summer School Phys. 17* (1976) p. 245; A. Chodos et al., Phys. Rev. D**9** (1974) 3471; *ibid.* **10** (1974) 2599; T. DeGrand *et al.*, *ibid.* **12** (1975) 2060.
[31] J. Bjorken, in *Proc. 3rd International Symposium on the History of Particle Physics: The Rise of the Standard Model, Stanford, CA, 1992*, eds. L. Hoddeson *et al.* (Cambridge Univ. Press, Cambridge, 1997) p. 589, and references therein.
[32] S. Jadach, B.F.L. Ward and Z. Was, Phys. Rev. D**88** (2013) 114022.
[33] D. Bardin *et al.*, JETP Lett. **96** (2012) 285; arXiv:1207.4400; S.G. Bondarenko and A.A. Sapronov, arXiv:1301.3687; L. Barze *et al.*, arXiv:1302.4606; C.M. Carloni-Calame *et al.*, J. High Energy Phys. **05** (2005) 019; G. Balossini *et al.*, J. Phys. Conf. Ser. **110** (2008) 042002; Y. Li and F. Petriello, Phys. Rev. D**86**(2012) 094034; V. A. Zykunov, Eur. Phys. J. C**3** (2001) 9; S. Dittmaier and M. Kramer, Phys. Rev. D**65** (2002) 073007; S. Dittmaier and M. Huber, J. High Energy Phys.**1001** (2010) 060; A. Denner *et al.*, J. High Energy Phys. **1106** (2011) 069; C. Bernaciak and D. Wackeroth, Phys. Rev. D**85** (2012) 093003.
[34] R. Aaij *et al.*, arXiv:1212.4620; J. Anderson and R. Wallace, LHCb-CONF-2013-007.
[35] S. Hassani, in Proc. Recntres de Moriond EW, 2013, in press; H. Yin, *ibid.*, 2013, in press; G. Aad *et al.*, arXiv:1211.6899.